

Protecting Keystone Species for Coastal Water Quality: Kelp Biofiltration in Municipal Wastewater Management

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Abstract

Eutrophication in water is a primary cause for degradation of marine environments, reducing biodiversity and diminishing water quality through excessive algal growth caused by nutrient enrichment. As nutrient enrichment continues to threaten water resources that can be used for human consumption, nurturing of kelps forests is seen as a promising solution. However, kelps are declining due to climate change, coastal pollution, overfishing, and overgrazing by sea urchin populations. As a keystone predator, sea otters regulate growing sea urchin populations and indirectly contribute to the growth and recovery of kelp. In this article, we examine the ecological significance of the sea otter – sea urchin – kelp trophic cascade, while analyzing the biofilter qualities of kelp, keeping the limitations in mind.

Introduction

Eutrophication, characterized by excessive algal growth due to nutrient enrichment, is one of the leading causes of aquatic ecosystem degradation. They severely impact biodiversity as they compete with other organisms for nutrients, limit light penetration, and disrupt aquatic food webs. As algae die, microbial decomposition consumes large amounts of dissolved oxygen, creating hypoxic or anoxic "dead zones" that are not conducive to many other aquatic life forms. In addition, many harmful algal species release toxins that degrade water quality and pose serious risks to human health. Although eutrophication is a natural process, nutrient pollution from agriculture, wastewater discharge, and urban development has greatly accelerated and promoted the process in areas where it previously didn't occur, threatening aquatic ecosystems and drinking water supplies (Chislock et al., 2013). Consequently, identifying sustainable methods to control nutrient pollution and algal proliferation has become an important rising priority to protect aquatic life forms and sources for drinking water. Recent research suggests that nurturing kelp forests may offer a promising ecological solution (Jiang et al., 2020).

Kelp are among the most ecologically important marine foundation species, serving as natural biofilters (Jiang et al., 2020). Kelps play a role in increasing dissolved oxygen in water while absorbing excess nutrients like nitrogen and phosphorus from the water, starving microalgae of the food they need to form massive blooms. In addition, their 3D dense and forest-like structures

also provide refuge, food and serve as nursing grounds for zooplankton species, predators of algae (Jiang et al., 2020).

Furthermore, Kelp absorbs atmospheric carbon dioxide and stores it as "blue carbon," reducing greenhouse gas concentrations while supporting marine carbon cycling (World Wildlife Fund, 2025). Healthy kelp forests can sequester substantial amounts of carbon in their biomass, much of which is transferred to marine sediments where it may remain stored for decades to centuries (Christensen et al., 2023).

Despite their ecological importance, kelp forests are declining worldwide due to climate change, coastal pollution, overfishing, and overgrazing by rapidly expanding sea urchin populations. Sea urchins are voracious herbivores that graze directly on kelp. When their populations become unchecked, they can completely strip kelp forests, transforming them into "urchin barrens" - rocky seafloors largely devoid of vegetation and biodiversity. Studies have consistently shown that kelp abundance increases as sea urchin populations decline (Stephens, 2022).

Sea otters are considered a keystone species because their ecological influence is disproportionately large relative to their abundance. As one of the primary predators of sea urchins, sea otters naturally regulate urchin populations through predation. By preventing excessive grazing, sea otters indirectly protect kelp forests, allowing them to grow, expand, and maintain their ecological functions (World Wildlife Fund, 2025).

This classic trophic cascade demonstrates how predator conservation indirectly protects kelp forests, enhances carbon storage, supports marine biodiversity, and contributes to climate change mitigation. By regulating sea urchin populations, sea otters allow kelp forests to thrive, enabling them to continue absorbing excess nutrients such as nitrogen and phosphorus from surrounding waters. This nutrient uptake may help reduce eutrophication, limit harmful algal blooms, and improve water quality.

Protecting sea otter populations therefore represents an effective ecosystem-based strategy for maintaining healthy kelp forests that support both marine biodiversity and nutrient regulation, addressing the underlying causes of wastewater-driven eutrophication.

Broader Impact

Relying on kelp forests to absorb nutrients requires that those forests be maintained, and the argument for maintaining them rests in part on the other services they provide. Several of these services have been quantified at a global scale.

Across six forest-forming genera, kelp forests have been valued at between \$64,400 and \$147,100 USD per hectare per year, with fisheries production and nutrient cycling accounting for most of that total (Eger et al., 2023). The nutrient component corresponds to 657 kg of nitrogen absorbed per hectare annually. This figure represents the nitrogen that a standing forest draws out

of the water column, which is a measure of filtration capacity and not of permanent removal. Kelp that is not harvested returns much of the nitrogen it absorbs once its tissue decomposes, so uptake and removal are distinct parameters. This distinction matters for wastewater applications, where a treatment system is evaluated on what it removes, whereas the economic valuation treats absorbed nitrogen as removed (Eger et al., 2023). Therefore, the requirements for harvesting are examined in the engineering section below.

The west coast of Vancouver Island forms a key example of economic assessment for the sea otter's role in maintaining these forests. The assessment compared a modelled otter-occupied coast against the same coast without otters, so the contrast is between presence and absence rather than between different otter densities. Under otter occupancy, total ecosystem biomass was 37% greater, producing annual gains of \$9.4 million in finfish value, \$2.2 million in carbon sequestration and \$42.0 million in ecotourism, against an annual loss of \$7.3 million to invertebrate fisheries (Grega et al., 2020). The net balance is a gain of roughly \$46 million per year, but the gains and losses fall on different groups. Shellfish and urchin harvesters bear the cost, while tourism revenue accrues more broadly.

Otter-driven kelp recovery also increases the carbon held in living biomass. Across the North Pacific this increase has been estimated at 4.4 to 8.7 teragrams of carbon, valued at \$205 to \$408 million USD at 2012 prices (Wilmers et al., 2012). The authors characterise it as a one-time change in standing stock rather than an annual flux, and note that it is unlikely to produce a measurable change in atmospheric carbon dioxide.

These estimates describe the value of kelp forests in financial terms. They do not establish whether the quantity of kelp that otter protection can realistically sustain is large enough to matter against the nitrogen load of a municipality. The following case study makes that comparison.

Case Study: Sea Otter Recovery on the West Coast of Vancouver Island

This coastline was selected for two reasons. It provides the clearest documented case of sea otter recovery restoring kelp forests, and it contains a coastal municipality whose nitrogen discharge can be compared against the area of kelp canopy growing nearby.

Sea otters were eliminated from British Columbia by 1929 through the maritime fur trade. Between 1969 and 1972, 89 animals were translocated from Alaska to Checleset Bay on the northwest coast of the island. The population has since grown beyond 3,000 and now occupies roughly 25 to 33% of its historical provincial range. Thirty years of subtidal survey data from this coast record the sequence predicted by trophic cascade theory, with urchin densities falling after otters arrived and kelp cover increasing afterward (Watson & Estes, 2011). Increases in kelp area are rarely reported anywhere on the North or South American coasts, and the documented

exceptions in Alaska and British Columbia coincide with sea otter population growth (Wachmann et al., 2026).

The effect is conditional, and two independent lines of evidence indicate why. A community model was applied to the Vancouver Island dataset alongside a comparable thirty-year dataset from San Nicolas Island in California (Langendorf et al., 2025). On Vancouver Island the cascade ran to completion, with urchins suppressed and kelp cover expanding in their place. Off California it stalled partway. Otters, urchins and kelp all persisted together at middling densities for several years, so barren ground never converted fully back into forest. Separately, a survey of 3,396 hectares of emergent kelp across 5,600 km of the Vancouver Island coast, compared against British Admiralty charts from 1858 to 1956, found that persistence over the past century was highest in cold, well-mixed water regardless of otter presence (Wachmann et al., 2026). One stretch of that coast with no established otter population retained 93% of its historical kelp, marginally more than an otter-occupied stretch at 91%.

These findings address different questions. The cascade studies measure whether urchin barrens convert back into kelp forest after otters arrive, whereas the persistence survey measures whether forests present in the nineteenth century still exist today. Otters restore kelp where grazing has removed it, and water temperature and mixing govern whether a forest survives over the long term. For wastewater applications this means that otter protection can maintain a filter but cannot establish one in unsuitable water, so kelp biofiltration would be viable only where local conditions already support kelp growth.

Clayoquot Sound, on the west coast of Vancouver Island in British Columbia, sits at the southern edge of the recovered otter range and contains a municipality with a documented discharge. That combination permits a comparison between the nutrient load a town produces and the uptake capacity of the kelp growing nearby. Nothing of the kind is in place there. No one routes the town's effluent toward the kelp beds, and the kelp forms no part of the municipal treatment system. The nitrogen load and the kelp uptake figures also come from separate studies using separate methods, so the comparison establishes the relative size of the two numbers and nothing about whether the kelp intercepts any of the discharge.

The District of Tofino discharged untreated sewage into Duffin Passage for decades. Water samples routinely exceeded coliform limits for recreational use and shellfish harvesting, producing closures that affected the Tla-o-qui-aht First Nation and local fisheries. A secondary treatment plant with ultraviolet disinfection became operational in 2024 at a capital cost of \$79.25 million (District of Tofino, 2024). The plant was designed to meet the federal Wastewater Systems Effluent Regulations, which set limits for carbonaceous biochemical oxygen demand, suspended solids, residual chlorine and un-ionized ammonia (SOR/2012-139). Total nitrogen is not regulated under those provisions, so most of the nitrogen in the effluent continues to enter Clayoquot Sound.

Tofino serves approximately 2,500 residents, two Tla-o-qui-aht communities and between 600,000 and 750,000 annual visitors. Applying standard per capita nitrogen generation rates of 8 to 14 g per person per day, we estimate an annual discharge of 15 to 49 tonnes of nitrogen. At the uptake rate reported above, absorbing that quantity would require 20 to 75 hectares of kelp forest (Eger et al., 2023). The Clayoquot subregion contains 304 hectares of mapped emergent kelp canopy (Wachmann et al., 2026), placing the town's entire nitrogen output at roughly 7 to 24% of the yearly nitrogen absorption capacity of that canopy.

This estimate indicates that the kelp population in this system is extensive enough for its nutrient uptake to be meaningful relative to a municipal load. It does not indicate that the kelp is treating Tofino's wastewater. Effluent disperses from the outfall and is not directed toward kelp beds, and uptake in Clayoquot Sound has not been measured against the discharge. This comparison only establishes potential capacity.

Tofino's decision to build the plant is consistent with that limit. The contamination that closed local shellfish beds was microbial, and kelp does not reduce fecal coliform concentrations. Capacity is also distinct from reliable operation. The following section examines seasonality, harvesting requirements and heavy-metal accumulation, which together determine whether a kelp forest could function as a component of a municipal wastewater system.

Real-World Engineering Constraints and Challenges

Seasonal Capacity Mismatch

When looking at water treatment systems that use nature-based solutions, an unexpected challenge appears. We are used to mechanical filters operating continuously, but biological filters work differently. Their performance depends on natural processes, which adds another layer of complexity.

Rather than providing a constant rate of filtration throughout the year, coastal kelp biofilters face a practical challenge. The periods when the greatest amount of pollution enters the water do not always match the periods when kelp is able to absorb nutrients most effectively.

During periods of heavy winter rainfall, stormwater overflows and wastewater outfalls release higher volumes of nitrogen and phosphorus into nearshore waters. However, this increase in pollution occurs at the same time that kelp biofiltration is at its weakest. Studies on kelp nutrient bioextraction show that nitrogen uptake rates peak during spring and summer growth windows, but drop significantly during the winter as colder water temperatures and reduced sunlight slow the kelp's metabolic activity (Kim et al., 2015).

Could the kelp compensate for this seasonal gap by storing extra nutrients during the summer? Unfortunately, giant kelp can only maintain internal nitrogen reserves for approximately 30 days. This means that it cannot “save up” enough summer capacity to compensate for several months of reduced winter growth (Zimmerman & Kremer, 1986).

However, reduced biological activity is only one part of the challenge. Winter storms can also physically damage the kelp forest itself. Strong waves and rough ocean conditions can tear away the upper fronds of the kelp forest, reducing the total amount of living biomass available to absorb nutrients when urban runoff is at its highest (Monterey Bay Aquarium, 2026). Long-term monitoring has shown that the productivity of giant kelp, *Macrocystis pyrifera*, depends heavily on how much of its canopy survives these winter disturbances (Santa Barbara Coastal LTER, n.d.).

These seasonal limitations mean that kelp biofilters cannot provide the same level of treatment year-round. Conventional systems may therefore be needed to manage higher winter pollution loads, while kelp provides additional nutrient removal during periods of stronger summer growth.

Nutrient Bioaccumulation vs. Permanent Removal

Although macroalgae can absorb excess nitrogen and phosphorus from the water, this raises an important question: are those nutrients permanently removed, or simply stored temporarily inside the kelp?

Giant kelp naturally loses and replaces its biomass throughout the year. As older fronds, the long, leaf-like blades that make up the kelp plant, break away, they may sink to the seafloor and begin decomposing. Microorganisms then break down the dead plant material and convert the stored organic matter back into inorganic nutrients. These nutrients, nitrogen and phosphorus, can then be released into the water again. Without harvesting, the kelp may only store the pollution temporarily before returning part of it to the surrounding environment (Fernandez, 2026).

So, should the kelp be harvested? And what does harvesting actually mean in this context?

Harvesting means using specialized vessels to trim and collect the grown kelp canopy, physically removing the nutrients stored inside it from the ocean. This process is already widely used in the global seaweed industry to produce products such as fertilizers and food thickeners, and some coastal cities, such as Long Island Sound, serving coastal Connecticut and New York

City, are now applying the same method to remove municipal pollution from nearshore waters (US EPA, 2020).

Harvesting nearshore kelp after a six- to seven-month growth period can remove between 19 kg and 176 kg of nitrogen per hectare (Grebe et al., 2021). This wide variation largely depends on local nutrient levels and growing conditions. Kelp deployed directly near urban wastewater outfalls absorbs significantly more nitrogen than kelp grown in cleaner, open waters. To put this into perspective, the upper end of this range is equivalent to the amount of nitrogen found in roughly 10 million litres of treated municipal wastewater (Government of Ontario, 2019).

However, harvesting the entire kelp forest would create a different environmental problem. Kelp forests provide food, shelter, and habitat for many marine species. Removing too much biomass could damage the same ecosystem the treatment system is intended to protect. This is another piece of the puzzle engineers must consider. Municipal kelp biofilters cannot be left completely unmanaged, but they also cannot be harvested without considering their ecological role. A possible approach is scheduled and rotational surface-canopy trimming. This would remove the upper, nutrient-rich fronds while preserving the lower parts of the kelp forest and allowing the system to continue growing.

Ecotoxicology and Heavy Metal Bioaccumulation

Using kelp as a natural biofilter offers a promising method for absorbing excess nitrogen and phosphorus, but what happens when wastewater contains more than nutrients?

Municipal and industrial wastewater, even after filtration, can often contain trace amounts of heavy metals, including cadmium, lead, copper, and mercury (Du et al., 2020). Kelps cell walls can bind to a variety of dissolved substances in the surrounding water, including toxic metals (Foday Jr et al., 2021).

Although this process can reduce the concentration of metals in the water column, it creates another environmental challenge. The pollutants have not disappeared. They have simply moved from the water into the kelp tissue.

Kelp is consumed by sea urchins and other marine invertebrates. If these organisms eat contaminated kelp, the metals can begin to accumulate inside their bodies. Predators, including sea otters, may then consume large amounts of these contaminated organisms. As the pollutants move through the food web, their concentrations may increase through a process known as biomagnification (National Oceanic and Atmospheric Administration, 2019).

Unlike nutrients, heavy metals are not easily broken down and can accumulate as they move through the food web. Their concentrations may increase at each level, exposing top predators to amounts that can cause immune-system damage and organ failure (Georgia Strait Alliance, 2018).

Because kelp cannot selectively absorb only harmless nutrients, any heavy metals present in the wastewater may also become trapped in its tissue and enter the marine food web. This means land-based pretreatment is necessary to remove toxic contaminants before the wastewater reaches the kelp biofilter.

Conclusion

As cities grow, more wastewater must be treated and released back into the environment. Even after treatment, some effluent may still contain nitrogen and phosphorus. Although these nutrients are necessary for aquatic life, excessive amounts can contribute to eutrophication and harmful algal blooms in coastal waters. Kelp offers a possible additional solution by acting as a biological sponge that absorbs these excess nutrients.

However, maintaining this natural biofilter depends on the surrounding ecosystem. By controlling sea urchin populations, sea otters help prevent kelp forests from being overgrazed. Protecting sea otters helps preserve the kelp biomass needed for nutrient uptake, along with the wider ecological and economic benefits that healthy kelp forests provide.

The Tofino case study shows both the potential and the limits of this approach. The town's estimated annual nitrogen output falls within the scale of what the surrounding kelp forest may absorb in a year. However, this does not mean that the kelp is currently treating Tofino's wastewater, since the effluent is not directed toward the kelp and actual uptake has not been measured. Tofino still required a \$79 million treatment plant because its main water-quality concern was microbial contamination, which kelp cannot remove. Conventional treatment and kelp biofiltration are therefore not competing solutions since they address different forms of pollution.

Kelp biofilters also come with important engineering challenges. Their nutrient uptake decreases during the winter, absorbed nutrients may return to the water unless the kelp is harvested, and heavy metals can become trapped in kelp tissue if the wastewater is not properly pretreated. For these reasons, kelp cannot replace conventional wastewater treatment. Its greatest value is as part of a layered system in which treatment plants remove pathogens and toxic contaminants, while kelp provides additional nutrient removal under suitable conditions.

Kelp cannot remove bacteria or toxic contaminants, while conventional treatment may still leave excess nutrients in the discharged water. This means that neither system can fully replace the

other, and they should instead work together so they can provide more complete treatment. This connects directly to the mission of The Student Water Project. Low-cost solutions are not only valuable in communities that lack major treatment infrastructure. They can also fill gaps in established systems, including those serving large cities. When used where they are most effective, practical technologies like kelp biofiltration can strengthen the entire water-treatment process.

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